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Predicting Concentration of Total Phosphorus and Chlorophyll 'a' in a Lake with Short Hydraulic Residence Time

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16. ABSTRACT

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The 1978-79 data were used in conjunction with the Vollenweider & Kerekes (1980) model to produce a model specific for the Skinner Lake system. The model predicted mean epilimnetic total phosphorus and chlorophyll a concentrations from mean total phosphorus concentration in inlet streams and from lake water residence time during the period of spring overturn and summer stratification. The Skinner-specific model was tested in 1982 and it closely predicted observed mean epilimnetic [TP] and [chl a] during the ice-free period. This study shows that variability in lake models which average data over an annual period can be reduced by considering lake-specific seasonal variation in hydrology and external TP loading.

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Predicting concentration of total phosphorus and chlorophyll *a* in a lake with short hydraulic residence time

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Keywords: lake model, total phosphorus, chlorophyll *a*, short hydraulic residence time

Abstract

The relationship between total phosphorus and chlorophyll *a* concentration was determined for Skinner Lake, Indiana over an annual cycle in 1978–79. Total nitrogen:total phosphorus ratios in the epilimnion ranged from 19 to 220 suggesting a phosphorus-dependent algal yield in the epilimnion. Approximately 90% of annual TP loading reached the lake via streamflow, and 93% of this entered during snowmelt and spring-overturn periods. At that time incoming water flushed the lake 2.4 times. Atmospheric loading accounted for 1.4% of annual TP load. Internal hypolimnetic TP loading occurred during summer stratification. Mean [chl *a*] for the ice-free period was 15.15 mg m^{-3}, within the range expected for eutrophic lakes.

The 1978–79 data were used in conjuction with the Vollenweider & Kerekes (1980) model to produce a model specific for the Skinner Lake system. The model predicted mean epilimnetic total phosphorus and chlorophyll *a* concentrations from mean total phosphorus concentration in inlet streams and from lake water residence time during the period of spring overturn and summer stratification. The Skinner-specific model was tested in 1982 and it closely predicted observed mean epilimnetic [TP] and [chl *a*] during the ice-free period. This study shows that variability in lake models which average data over an annual period can be reduced by considering lake-specific seasonal variation in hydrology and external TP loading.

Introduction

Lake modeling based on nutrient loading has its historical roots in the work of Sawyer (1941) who used this concept to study the effects of agricultural and urban drainage on lake fertility. He observed the greatest and the most frequent algal blooms in lakes which received the greatest quantities of phosphorus and nitrogen. Rawson (1955) and Edmondson (1961) later reported that mean depth was also an important factor related to lake productivity. This factor took into account the degree of dilution of nutrients entering from the watershed. Vollenweider (1968) combined the factors of nutrient loading and lake depth and quantitatively modeled the planktonic algal response of phosphorus limited lakes. Vollenweider's model predicted that lakes with similar planktonic algal production had similar ratios of total phosphorus loading (mg P m^{-2} a^{-1}) to mean depth. Vollenweider (1975, 1976) revised his phosphorus loading model to include hydraulic residence time and phosphorus residence time to account for the effects of flushing rate and phosphorus sedimentation on nutrient loading – trophic response relationships. A current revision (Vollenweider & Kerekes, 1980) was based on data from 200 lakes in 50 countries participating in the Organization for Economic Cooperation and Development (OECD) Cooperative Program on Lake Eutrophication. Vollenweider & Kerekes (1980) reported that hydraulic residence time and phosphorus residence time were key factors and related in the following manner:

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$$t_p : t_w \propto \frac{[\overline{TP}_L]}{[\overline{TP}_i]} \cong \frac{1}{1 + t_w^{1/2}}$$

and

$$[\overline{TP}_L] \cong \frac{[\overline{TP}_i]}{1 + t_w^{1/2}} \quad (1)$$

where t_p is the residence time of phosphorus, t_w is the hydraulic residence time, $[\overline{TP}_i]$ is the mean incoming phosphorus concentration and $[\overline{TP}_L]$ is the mean lake phosphorus concentration. This model, in which annual mean in-lake phosphorus concentration is related to mean incoming phosphorus concentration on an annual basis, is the same as that developed by Larsen & Mercier (1976) and is similar to those developed by Kirchner & Dillon (1975), Chapra (1975), Reckhow (1977) and Walker (1977). From the OECD data, Vollenweider & Kerekes (1980) also presented an equation relating total lake phosphorus concentration and algal production as measured by chlorophyll *a* concentration:

$$\log [\overline{chl\ a}] = 0.99 \log [\overline{TP}_L] - 0.57 \quad (2)$$

where $[\overline{chl\ a}]$ is mean chlorophyll *a* concentration and $[\overline{TP}_L]$ is mean in-lake total phosporus concentration. Since the time that equations (1) and (2) were presented by Vollenweider & Kerekes (1980), another version of this phosphorus model was reported (OECD 1982). The latest model differs only in the values of constants, and we utilized the 1980 model to represent the conceptual framework around which we based the following study.

In the study reported herein, variables of the Vollenweider & Kerekes (1980) model were measured on Skinner Lake in northeastern Indiana. The original model was modified to fit conditions found in Skinner Lake, and a specific model for Skinner Lake system resulted. The predictive value of the Skinner-specific model was subsequently tested by altering the total mean phosphorus input to the lake ($[\overline{TP}_i]$ of equation (1)) and monitoring the planktonic algal response. The alteration in TP inputs was accomplished by implementation of agricultural land management practices on the watershed.

Description of study area

Skinner Lake is located in Noble Co., Indiana, U.S.A. It has an average depth of 4.4 m, a maximum depth of 10 m and a surface area of 49.4 ha. Water level is controlled by a concrete sill dam constructed in 1962. The lake discharges to Croft Drain which enters the South Branch of the Elkhart River. One hundred and twenty-five permanent residences line the lake shore.

Thermal stratification of Skinner Lake existed from mid-May through mid-October in the years 1978 and 1979 and the hypolimnion reached anaerobic conditions rapidly as stratification became established. Relative areal oxygen deficits, calculated for the interval 1 May through 15 May in 1978 and 1979 ranged from 700–900 mg m^{-2} d^{-1} and this places Skinner Lake in the eutrophic category based on Hutchinson's (1957) criterion. Other evidence of eutrophic conditions in Skinner Lake included extensive growth of aquatic macrophytes, such as *Nymphaea odorata, Ceratophyllum demersum,* and *Myriophyllum spicatum*, and blooms of blue-green algae (*Aphanizomenon* sp.). Dominant fish in Skinner Lake included sunfish (*Lepomis* spp.) and crappies (*Pomoxis* spp.), and a large rough fish population composed of the white sucker (*Catastomus commersoni*) and the golden shiner (*Notemigonus crysoleucas*). A general decline in fishing quality in Skinner Lake over the last two decades has been attributed to turbidity, low oxygen conditions and large amounts of algae and macrophytes (Pearson 1978).

The Skinner Lake watershed consists of 3649 ha, of which 68% is agricultural land and 32% is forest and wetlands. The Rimmell inlet drains 82% (3091 ha) of the Skinner Lake watershed. Land within the Rimmell drainage system is put to varied crop and livestock use and subsurface tiles are widely employed for drainage. Four smaller streams carrying tile and surface runoff enter the lake from agricultural land.

Methods

Studies were conducted at Skinner Lake from September 1978 to September 1979 to determine $[\overline{TN}_L]$, $[\overline{TP}_L]$, t_w and $[\overline{chl\ a}]$ of the Vollenweider & Kerekes model (equations (1) and (2)). Water sam-

ples were collected at two-week intervals in the ice-free period to determine $[\overline{TN}_L]$ and $[\overline{TP}_L]$. A volume-proportional scheme was used to obtain representative samples of upper pelagial portions of the lake. During summer stratification, these zones were the epilimnion and hypolimnion respectively. Volumes of water within layers of the upper and lower zones were calculated from:

$$V = \frac{h}{3}(A_1 + A_2 + (A_1 A_2)^{1/2}) \quad (3)$$

where h was depth of a layer of water, A_1 was area of the upper surface of that layer, and A_2 was the area of the lower surface of that layer (Wetzel 1975). A bathymetric map of the lake was used to obtain areas. Three strata within the upper pelagial water were sampled at four stations on the lake, and combined to form the volume-proportional composites. Similarly, water was combined from three strata in the lower pelagial zone. The composite samples were obtained in duplicate.

Total phosphorus and total nitrogen concentrations were determined in these composite samples using procedures described in U.S. EPA Methods for Chemical Analysis of Water and Wastes (1979a).

$[\overline{TN}_L]$ and $[\overline{TP}_L]$ for Skinner Lake were calculated with the following equation:

$$[N_L] = \frac{(V_{up}[N]_{up}) + (V_{low}[N]_{low})}{V_L} \quad (4)$$

where V_{up} was volume of the upper pelagial at sampling time, $[N]_{up}$ was nutrient concentration determined from upper pelagial composite sample, V_{low} is volume of the lower pelagial at sampling time, $[N]_{low}$ is the nutrient concentration determined from the lower pelagial composite sample, and V_L is volume of Skinner Lake (2.157×10^6 m^3). Ratios of total nitrogen to total phosphorus ($[TN_L]$:$[TP_L]$) were calculated using these values. Mean in-lake concentrations over the ice-free period were calculated by finding the average of the nutrient values as calculated by equation (4).

Measurements of atmospheric loading, stream loading and internal loading to Skinner Lake were made to estimate $[\overline{TP}_i]$ for the model.

Total phosphorus concentration in atmospheric fallout was determined at intervals of two to several weeks according to the method of Batterson & McNabb (1983). Triplicate lexan containers (23 cm deep, area = 0.26 m^2) in a stand 1 meter above the surface of the lake, were used to collect fallout. At the begnning of each period, acid cleaned containers were filled with six liters of distilled deionized water. One liter was withdrawn from each. These were combined and analyzed for beginning concentrations of TP. After exposure, interior surfaces of containers were cleaned into the water. Water from all containers was combined and mixed. Volume was measured, and 1 l was withdrawn for analysis of [TP]. Loading was calculated from the increase in mass in TP during the period of exposure.

Stream [TP] for September 1978–September 1979 was based on a water budget for that interval. Continuous hourly stage height records were available for the two streams with greatest discharge, the Rimmell stream and Croft Drain. Largest fluctuations of discharge occurred during spring. On the basis of these data, daily flow measurements were made during the spring of 1979 to estimate discharge for streams without recorders. During the rest of 1978–79, when fluctuations in discharge were small, flows on these streams were measured at two-week intervals. Discharge rates were determined according to the U.S. Dept. of Interior Water Measurement Manual (1967) using a pygmy Price-Gurly current meter. Hydrographs were constructed for all streams. Stream discharges for the whole year (9/6/78–10/3/79), and periods of snowmelt-spring overturn-summer stratification (2/6–10/3/79), spring overturn-summer stratification (3/20–10/3/79), and summer stratification (5/21–10/3/79) were determined by planimetry of the stream hydrographs.

[TP] was measured in stream samples collected daily during spring of 1979. Aliquots from each stream's samples were composited over two-weeks according to the discharge-proportional scheme of Glandon *et al.* (1981). During summer, fall and winter, individual samples were collected for [TP] at two-week intervals.

Mass of TP for each inlet was calculated by multiplying concentration by the total discharge of the inlet over intervals represented by water samples. Mean concentration of total phosphorus in stream flow discharge to Skinner Lake ($[\overline{TP}_i]$) was calculated by adding amounts of TP in discharge of five inflows to the lake and dividing by total volume of discharge of those streams over the interval in question.

Internal loading of TP was estimated from:

$$TP_{load} = \Delta \text{ Lake Storage} - (TP_{in} - TP_{out}) \quad (5)$$

where TP_{Load} was mass of TP internally loaded to Skinner Lake during an interval, TP_{in} was the mass of TP entering in flow of stream, TP_{out} was mass of TP exiting the lake, and Δ Lake Storage was the difference in mass the lake contained between the beginning and end of an interval. TP_{Load} calculated for the ice-free season up until mid-July was zero or negative. TP_{Load} calculated for the remainder of the stratification period (7/16–10/3) was large and positive. Solving the equation for the interval 7/16–10/3/79 allowed for determination of the mass of TP in the lake due to internal loading.

Year around distribution of temperature and dissolved oxygen was measured in Skinner Lake to mark the times of occurrence of overturn and depths of the epilimnion, metalimnion, and hypolimnion during summer stratification. Dissolved oxygen and temperature were measured at two-week intervals at each of four lake sampling stations during the ice-free season. These measurements were taken at 0.5 m depth intervals with a YSI Model 54A oxygen meter.

Flushing coefficient (ρ) and residence time of water (t_w) were calculated for Skinner Lake. The flushing coefficient was determined as:

$$\rho = V_O V_L^{-1} \quad (6)$$

where V_O was volume of outflow from the lake, and V_L was volume of the lake. Planimetry of the hydrograph of the Croft Drain outlet yielded lake discharge. Flushing coefficients were calculated for intervals of the year and for a whole year (9/6/78–9/17/79). The flushing coefficient for the epilimnion (to 4 m depth) during summer stratification was also calculated. Residence time (t_w) is the reciprocal of the flushing coefficient.

Chlorophyll *a* concentrations in Skinner Lake were measured for use in the Vollenweider & Kerekes expression of equation (2). Upper pelagial composite samples were collected at two-week intervals during the ice-free period of 1979. Chlorophyll *a* was determined as outlined in Strickland & Parsons (1972).

Land management practices were instituted on the Skinner Lake watershed during 1979–1981 with cost-sharing funds provided by the U.S. EPA under the Clean Lakes Program (U.S. EPA 1979b), and U.S. Department of Agriculture, Soil Conservation Service. The particular practices used were chosen from the data and experience generated by the non-point-source pollution study of Black Creek in nearby Allen County, Indiana (Christensen & Wilson 1979; Lake & Morrison 1977). These included settling basins, conservation tillage, group tile mains, terraces, livestock exclusion, planting vegetation on critical sites, diversions, and grassed waterways. The goal of these practices was to decrease nutrient runoff to Skinner Lake and ultimately reduce blue-green algal blooms which occurred each summer. The anticipated reduction of $[TP_i]$ due to land management provided the opportunity to evaluate the predictive value of the Skinner Lake model.

During 1982, measurements of $[TP_i]$ due to streams and t_w were done as in 1978–79. The period 3/24–9/13/82 was used for making measurements to test a Skinner-specific lake model. This was justified because data from 1978–79 showed that $[\overline{TP}_i]$ and t_w calculated over the spring overturn-summer stratification interval determined $[\overline{TP}_L]$ in the ice-free period, and that algal production in the ice-free period was related to $[\overline{TP}_L]$ by equation (2). Samples from the lake's outflow were taken from 3/24–9/13/82 to determine $[\overline{TP}_L]$ and $[\overline{\text{chl } a}]$. Mean [TP] of the epilimnion during summer of 1979 ($\bar{x} = 44$ mg m^{-3}, $s = 16$, $n = 12$) was essentially the same as that of Skinner Lake's outflow ($\bar{x} = 45$ mg m^{-3}, $s = 27$, $n = 12$). This followed the prediction of Chapra (1975) that the concentration of outflowing water will be essentially equivalent to that in the epilimnion of mid-lake in small systems.

Results

Concentrations of nitrogen and phosphorus in Skinner Lake in 1979 are reported in Table 1. The observed range of [TN] was 1.19–5.88 mg l^{-1} and [TP] from 0.021–0.199 mg l^{-1}. High whole-lake [TP] during the time July 30–October 3 resulted primarily from high TP concentration in the hypolimnion. These ranged from 0.154–0.221 mg l^{-1} during that time and apparently were result of phosphorus release across the anaerobic sediment surface of the hypolimnion. It can be noted from Table 1 that concentrations of TP in the epilimnion from July 30–October 3 were approximately 50% of

Table 1. Concentrations of nitrogen and phosphorus (mg l^{-1}) in Skinner Lake during the ice-free period in 1979. [TN]:[TP] are given for whole lake during spring and fall overturns and epilimnion during summer stratification.

Date	Whole lake		Hypolimnion[a]		Epilimnion[a]		
	[TN]	[TP]	[TN]	[TP]	[TN]	[TP]	[TN]:[TP]
March 19	5.85	0.199					29
April 1	5.88	0.177					50
April 15	5.42	0.093					58
April 23	5.61	0.068					83
May 7	4.50	0.047					96
May 21	4.54	0.055	4.44	0.075	4.65	0.031	150
June 5	3.57	0.036	2.52	0.050	4.61	0.021	220
June 18	3.42	0.037	3.82	0.045	2.92	0.027	108
July 2	2.95	0.067	2.97	0.078	2.94	0.060	49
July 16	2.75	0.042	2.58	0.062	2.90	0.024	121
July 30	3.28	0.081	2.93	0.154	3.50	0.034	103
August 13	1.94	0.137	2.78	0.211	1.19	0.062	19
August 21	1.91	0.106	2.74	0.198	1.48	0.059	25
September 17	2.69	0.121	3.81	0.203	1.69	0.048	35
October 3	1.82	0.120	2.50	0.196	1.20	0.052	23
October 24	1.28	0.043					30
November 14	1.38	0.036					32
December 12	3.07	0.044					70
Means	3.44	0.081	3.11	0.128	2.71	0.042	72

[a] Lake stratified May 21 through October 3.

whole-lake concentrations during that time. Whole-lake [TP] changed abruptly in October with initiation of fall overturn, falling from 0.120 to 0.043 mg l^{-1}. The concomitant decrease in [TP] with fall overturn suggested that phosphorus, particularly that in the hypolimnion, fell out to the sediments. This suggestion was supported by solving equation (5) for phosphorus mass balance in the lake basin for the period when fall overturn was initiated (October 3–October 24).

Internal phosphorus loading estimates in 1979 were negative from ice-out until mid-July, indicating a net loss of phosphorus. For the interval July 16–October 3, internal loading to the water column was calculated to be 120 kg TP.

Total nitrogen: total phosphorus ratios for the epilimnion of Skinner Lake ranged from 19–220 (Table 1) indicating that algal yield in the epilimnion was likely phosphorus dependent based on the criteria of Sakamoto (1966), Chiaudani & Vighi (1974), Allan & Kenny (1978), Smith & Shapiro (1981) and Smith (1982).

Atmospheric bulk loading measurements of TP on Skinner Lake for the study interval of 1978–1979 are given in Table 2. Atmospheric loading amount-

Table 2. Atmospheric bulk loading of total phosphorus on Skinner Lake during the interval 9/6/78–9/17/79.

Period	Rate of fallout (mg m^{-2} d^{-1})	Input to lake (kg d^{-1})
9/16 – 9/25/78	0.099	0.049
9/25 – 10/ 9/78	0.045	0.022
10/ 9 – 10/23/78	0.117	0.058
10/23 – 11/ 6/78	0.066	0.033
11/ 6 – 11/27/78	0.050	0.024
11/27 – 12/14/78	0.092	0.045
12/14 – 1/ 6/79	0.041	0.020
1/16 – 2/ 6/79	0.023	0.011
2/ 6 – 4/ 2/79	0.074[a]	0.036[a]
4/ 2 – 4/23/79	0.125	0.061
4/23 – 5/ 7/79	0.107	0.052
5/ 7 – 5/21/79	0.378	0.185
5/21 – 6/18/79	0.145	0.071
6/18 – 7/ 2/79	0.108	0.053
7/ 2 – 7/16/79	0.059	0.029
7/16 – 7/30/79	0.126	0.062
7/30 – 8/13/79	0.607	0.298
8/13 – 8/27/79	0.222	0.109
8/27 – 9/17/79	0.163	0.080

[a] Sampling disrupted: values are the average between the previous and following intervals.

Table 3. Flushing coefficients (ρ of equation 6) of Skinner Lake during periods of 1978–79.

Period	ρ
Fall overturn and winter	
9/6/78 – 2/6/79	0.02
Snow melt	
2/6 – 3/20/79	1.30
Spring overturn	
3/20 – 5/22/79	1.06
Summer stratification	
5/22 – 9/6/79	0.17
Whole year	
9/6/78 – 9/6/79	2.55

ed to 0.04 g TP m^{-2} year. This measurement fell within the range predicted for the region by Chapin & Uttormark (1973), and constituted 1.4% of the annual stream loading.

Stream hydrographs for the period 1978–1979 were divisible into periods of fall and winter runoff, runoff due to snowpack melt, discharge during spring overturn, and discharge during summer stratification. Total discharge associated with snowpack melt contributed 53% of annual stream discharge to Skinner Lake in 1978–79. Stream discharge from rains during spring overturn contributed 35% of annual discharge. Base flows of summer, fall and winter provided 12% of annual runoff to the lake.

Flushing coefficients (ρ) for Skinner Lake for periods during 1978–79 are given in Table 3. Runoff from snowmelt displaced the volume of water in the lake 1.3 times. Subsequent runoff from rains diluted the lake during spring overturn. The low summer stream discharges were reflected in the low flushing coefficient during stratification.

Phosphorus carried by spring runoff dominated stream $[\overline{TP}_i]$ during the 1978–79 annual interval. Ninety-three percent of annual TP loading was delivered to Skinner Lake through the five inlets during the snowmelt and spring overturn periods (February–May). Calculated stream $[\overline{TP}_i]$ was 321 mg m^{-3} for 1978–79.

The 1982 post-land-treatment measurements were used to test the Skinner Lake model. During the interval of measurement in 1982, t_w was 0.65, $[\overline{TP}_i]$ from streams was 99.6 mg m^{-3}, and $[\overline{TP}_L]$ was 54 mg m^{-3}. For the comparable interval in 1979, t_w was 0.63, $[\overline{TP}_i]$ from streams was 127 mg m^{-3} and $[\overline{TP}_L]$ was 63 mg m^{-3}. By the relationship of equation (2), $[\overline{chl\ a}]$ in the ice-free period was expected to be less in 1982 than in 1979. Chlorophyll data for these years are given in Table 4. As predicted, a decrease in $[\overline{chl\ a}]$ from 15.15 mg m^{-3} to 9.58 mg m^{-3} occurred between years.

Table 4. Concentration of chlorophyll *a* (mg m^{-3}) in Skinner Lake during summer of 1979 and 1982.

1979		1982	
Date	[chl *a*]	Date	[chl *a*]
4/23/79	24.80		
5/ 7/79	11.59	5/ 4/82	7.48
5/21/79	6.27	5/18/82	4.01
6/18/79	12.05	6/ 2/82	8.01
7/ 2/79	18.96	6/18/82	9.35
7/16/79	9.36	6/28/82	5.34
7/30/79	13.26	7/14/82	16.02
8/13/79	12.21	7/28/82	16.02
8/27/79	20.42	8/10/82	9.35
9/17/79	16.70	9/13/82	10.68
10/ 3/79	21.00		
	$\bar{x}$ = 15.15		$\bar{x}$ = 9.58

Discussion

The Vollenweider & Kerekes model was applied to the Skinner Lake system to quantify the relationship of $[\overline{TP}_i]$ to $[\overline{TP}_L]$ and $[\overline{chl\ a}]$. From 1978–79 data of this study, their model was specifically modified to fit the conditions of Skinner Lake. To make these modifications, the following parameters were considered: major sources of $[TP_i]$, seasonal differences in $[TP_i]$ and t_w, and differences in epilimnetic and hypolimnetic $[TP_L]$ and their relation to $[\overline{chl\ a}]$.

Vollenweider and Kerekes (1980) did not specify the sources of $[TP_i]$ measured to derive the empirical basis for their model. Several potentially important sources of $[TP_i]$ are atmospheric loading, septic tank loading, internal loading, and stream loading and these were evaluated as to their relative importance in Skinner Lake. The influence of atmospheric TP loading on $[\overline{TP}_i]$ of Skinner Lake was small (1.4% of annual stream loading). Septic tank loading to Skinner Lake was estimated using the constant, 0.08 kg TP $caput^{-1}$ a^{-1}, reported by Walker (1979). The approximately 375 people served by septic tanks around Skinner Lake contributed 30 kg TP a^{-1} or 2% of the 1978–79 annual total TP load. During summer of 1979, the estimat-

Table 5. Fit of Skinner Lake data of 1978–79 to Vollenweider & Kerekes (1980) estimates of in-lake $[\overline{TP}]$ calculated from:

$$[TP_L] = \frac{[\overline{TP}_i]}{1 + t_w^{1/2}}$$

where $[\overline{TP}_i]$ is from stream discharges except for case III B.

	Period		$[\overline{TP}_i]$ (mg m^{-3})	t_w (period)	Predicted $[\overline{TP}_L]$ (mg m^{-3})	Observed $[\overline{TP}_L]$ (mg m^{-3})
I.	Whole year					
	9/6/78 – 10/3/79		231	0.39	142	85
II.	Snowmelt-spring overturn-summer stratification					
	2/6 – 10/3/79		234	0.41	143	98
III.	Spring overturn-summer stratification					
	3/20 – 10/3/79	(A)	127	0.63	71	88
		(B)	163[a]	0.63	91	88
		(C)	127	0.63	71	63[b]
IV.	Summer stratification[c]					
	5/22 – 10/3/79		89	3.38	31	80

[a] Internal loading was added to stream loading to calculate $[\overline{TP}_i]$.

[b] Observed $[\overline{TP}_L]$ was calculated by averaging whole lake $[\overline{TP}_L]$ for the period of spring-overturn that constitutes one flushing time prior to stratification and epilimnetic $[\overline{TP}_L]$ during summer stratification.

[c] Whole-lake volumes and concentrations were used to calculate $[\overline{TP}_L]$.

ed 120 kg of internal TP loading comprised 8% of the 1978–79 total TP load. Stream loading was by far the major component of $[\overline{TP}_i]$ at Skinner Lake, comprising 90% of the annual TP input. Because stream loading and internal loading were the predominant sources of phosphorus for Skinner Lake, the following discussion of models is based on them at the exclusion of atmospheric and septic tank loading.

Vollenweider & Kerekes calculated $[\overline{TP}_i]$ and $[\overline{TP}_L]$ by averaging data over an annual period. However, in the Skinner Lake system there was great seasonal variation in both $[\overline{TP}_i]$ and t_w over a year and these variations affected the model's predictions of $[\overline{TP}_L]$ as can be seen in Table 5. Base flow conditions of streams in fall and early winter (9/6/78–2/5/79) had little influence on the magnitude of $[\overline{TP}_i]$ and t_w. The Vollenweider & Kerekes model greatly overestimated $[\overline{TP}_L]$ for the whole year and for the period including snowmelt, spring overturn and summer stratification. The snowmelt period greatly influenced the magnitude of $[\overline{TP}_i]$ and t_w as can be seen by comparing Rows II and III of Table 5. During the time of melting snow (2/6–3/20/79) both [TP] and discharge of inlet streams were high. Estimates of $[\overline{TP}_i]$ and t_w taken for the spring overturn and summer stratification period provided a better prediction of $[\overline{TP}_L]$ of the Vollenweider & Kerekes model than estimates of variables using other periods of the year (Row III, Table 5). Predicted $[\overline{TP}_L]$ from $[\overline{TP}_i]$ and t_w during summer stratification underestimated observed $[\overline{TP}_L]$ (Row IV, Table 5).

The Vollenweider & Kerekes model assumes that [TP] is homogeneously distributed in a lake's water column. However, Skinner Lake did not follow this assumption in that hypolimnetic [TP] was more than twice epilimnetic [TP] during the last half of the summer stratification period. In this study whole-lake $[\overline{TP}_L]$ was calculated for the spring overturn-summer stratification period using TP mass and volume of water in both the epilimnion and hypolimnion. This yielded a $[\overline{TP}_L]$ for the period of 88 mg m^{-3}. Row IIIA of Table 5 shows that whole-lake $[\overline{TP}_L]$ was underestimated using the Vollenweider & Kerekes model with measured values of $[\overline{TP}_i]$ and t_w. Whole-lake $[\overline{TP}_L]$ was more accurately predicted by including internal TP load with stream TP load in the $[\overline{TP}_i]$ term (Row IIB, Table 5). This was accomplished by adding the 120 kg of 1979 internal load to TP mass from stream load and dividing by stream discharge. This better fit suggests that $[\overline{TP}_i]$ should include both stream and internal loading when predicting whole-lake

$[\overline{TP}_L]$ for Skinner Lake during the spring-summer interval.

A major goal and practical application of this study was to predict the production of algae as measured by $[\overline{chl\ a}]$ in Skinner Lake. To predict $[\overline{chl\ a}]$ during the ice-free season, $[\overline{TP}_i]$ and $[\overline{TP}_L]$ were used in equation (2) of the Vollenweider & Kerekes model. Using whole-lake $[\overline{TP}_L]$ measured in the spring-summer period, 1979, predicted $[\overline{chl\ a}]$ in Skinner Lake was 22.65 mg m^{-3}. This overestimated the observed value of 15.15 mg m^{-3}. On the assumption that algae grow in response to [TP] of the epilimnion (Smith & Shapiro 1981), an alternate method was used to calculate $[\overline{TP}_L]$ for Skinner Lake. This method used the average of whole-lake [TP] during spring overturn and epilimnetic [TP] during summer stratification (Table 1). The resulting $[\overline{TP}_L]$ for 1979, designated as $[\overline{TP}_{epi}]_{ss}$, was 63 mg m^{-3}. Using $[\overline{TP}_{epi}]_{ss}$ value in equation (2) predicted $[\overline{chl\ a}]$ at 16.27 mg m^{-3}, much closer to the observed value given above. Thus, while including internal loading in $[\overline{TP}_i]$ for the spring-summer period yielded a close approximation between predicted and observed whole-lake $[\overline{TP}_L]$, $[\overline{chl\ a}]$ was best predicted by $[\overline{TP}]$ in the whole lake at overturn and the epilimnetic $[\overline{TP}]$ in summer. Row IIIC of Table 5 shows that $[\overline{TP}_i]$ for streams in spring-summer predicted observed $[\overline{TP}_{epi}]_{ss}$ relatively well. Based on these considerations, $[\overline{TP}_i]$ of Vollenweider & Kerekes was treated as $[\overline{TP}_{stream}]_{ss}$ and $[\overline{TP}_L]$ as $[\overline{TP}_{epi}]_{ss}$ for purposes of modeling the effect of incoming phosphorus on algal yield in Skinner Lake. Further, a spring overturn period was used in 1979 to coincide with the interval of time prior to stratification during which the flushing coefficient of the lake approximated 1.0. This defined the spring period as applied to the variables in the Skinner-specific model. This approach is similar to that presented by Ryding & Forsberg (1980). Records for the U.S. Weather Bureau for 1979 showed it was a relatively dry year at Skinner Lake. Basing a model on a spring period where $\rho = 1$ appeared appropriate for this system.

Based on the above considerations, the Skinner-specific model became:

$$[\overline{TP}_{epi}]_{ss} = \frac{[\overline{TP}_{stream}]_{ss}}{1 + t_{w_{ss}}^{1/2}} \qquad (7a)$$

$$\log [\overline{chl\ a}] = 0.99 \log [\overline{TP}_{epi}]_{ss} - 0.60 \qquad (7b)$$

where $[\overline{TP}_{epi}]_{ss}$ was mean TP concentration of the epilimnion over the spring-summer stratification (ss) interval, $[\overline{TP}_{stream}]_{ss}$ was mean TP concentration delivered to the lake from the inlet streams over the ss interval, $t_{w_{ss}}$ was residence time of water in the lake over the ss interval, and $[\overline{chl\ a}]_{ss}$ was mean chlorophyll *a* concentration in the epilimnion over the ss interval. The constant in the Vollenweider & Kerekes relationship for $[\overline{chl\ a}]$ and $[\overline{TP}_L]$ given in equation (2) was changed from 0.57 to 0.60 to fit the observed conditions of Skinner Lake during 1978–79.

Following agricultural management during 1979–1981, the Skinner-specific model proved to be an accurate predictor of $[\overline{TP}_{epi}]_{ss}$ and $[\overline{chl\ a}]_{ss}$. In 1982 $[\overline{TP}_{stream}]_{ss}$ was 100 mg m^{-3} as compared to 127 mg m^{-3} in 1979. Concomitant decreases in $[\overline{TP}_{epi}]_{ss}$ and $[\overline{chl\ a}]_{ss}$ were expected as predicted by equations (7a) and (7b). Predicted $[\overline{TP}_{epi}]_{ss}$ for 1982 was 55 mg m^{-3}; observed was 54 mg m^{-3}. Predicted $[\overline{chl\ a}]_{ss}$ was 13.02 mg m^{-3}; observed was 9.58 mg m^{-3}.

Figure 1 illustrates the Skinner-specific model.

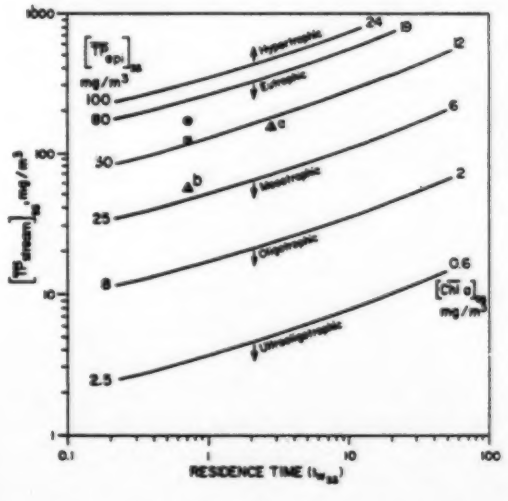

Fig. 1. Diagramatic representation of the Skinner-specific model (modified from Vollenweider & Kerekes, 1980). ● represents plot of Skinner Lake coordinates of 1979; ■ represents plot of Skinner Lake coordinates of 1982; $\triangle^a$ probable case for Skinner Lake with diversion of Rimmell stream around lake to outlet stream; $\triangle^b$ probable case for Skinner Lake if settling basin on Rimmell stream removed 100% of particulate phosphorus in stream discharge.

Given $[\overline{TP}_{stream}]_{ss}$ and t_w, $[\overline{TP}_{epi}]_{ss}$ can be predicted. Curves across the figure give expected $[\overline{chl\ a}]_{ss}$. Included on Figure 1 are plots of Skinner Lake data for 1979 and 1982. Figure 1 shows the observed improvement in the condition of Skinner Lake between 1979 and 1982. Reduction in $[\overline{TP}_{stream}]_{ss}$, $[\overline{TP}_{epi}]_{ss}$ and $[\overline{chl\ a}]_{ss}$ occurred. This improvement was due to land management practices implemented on the watershed during 1978–1981, and/or to ordinary between-year variability in the systems. It should be noted, that by definition of variables in the Skinner Lake model, comparable portions of the water-year in 1979 and 1982 were used in this study, as indicated by tw_{ss} values of 0.63 in 1979 and 0.65 in 1982. Unusually intense storms did not occur in those intervals in either year. Therefore it is probable that land management was the primary cause for the improvement observed in Skinner Lake during this study. However, ordinary between-year variability was not measured in the system during years prior to land treatment, and only a continuing trend of improvement with maintenance of existing practices and implementation of others on the watershed in the years ahead will confirm this.

In the use of models such as have been discussed, a range of uncertainty exists within which predicted values vary from observed. This uncertainty may reduce the power of conclusions which are based on lake modeling schemes (Reckhow 1981). In order to calculate confidence limits of model predictions, it is necessary to determine standard error from the variation among lakes used to construct the particular model. Two current lake models (Reckhow, 1977 and Walker, 1979) consider the statistical uncertainty of predictions of lake phosphorus concentrations, and both give a method by which confidence limits can be calculated. Confidence intervals for predictions made be these models can be estimated from:

$$S_t^2 = | P_e - 10^{\log P_e \pm s_m} |^2 \qquad (8)$$

where S_t is the total prediction error in mg l^{-1}, s_m is the standard error of the estimate for the model, and P_e is the predicted lake concentration (Reckhow 1981). Table 6 compares predictions made by the Skinner-specific, Reckhow (1977) and Walker (1977) models for phosphorus in Skinner Lake in 1979. For the purpose of this comparison, $[\overline{TP}_i]$ was taken as $[\overline{TP}_{stream}]_{ss}$, and $[\overline{TP}_L]$ as $[\overline{TP}_{epi}]_{ss}$ in the Reckhow and Walker models. Table 6 also presents the predicted confidence intervals of these models. In both cases, the confidence intervals are wide, and it is difficult to apply them to a particular lake for management decision purposes. It should be noted that error terms were estimated from least squares analysis on a data set from many lakes. Thus, much of the error results from variability between these lakes (Reckhow 1977). When a model is applied to a particular lake, the model error term should only include that lake's variability. For example if the Skinner-specific model could be applied to Skinner Lake for several years, a series of predicted and observed values would allow deter-

Table 6. Comparison of the predictions of $[\overline{TP}_L]$ from $[\overline{TP}_i]^a$ and t_w using three models. Observed lake concentration[b] = 63 mg m^{-3}.

Model and S_m[c]	Model equation[d]	Predicted $[\overline{TP}_L]$ (mg m^{-3})	Confidence limit (mg m^{-3})
Skinner-specific	$[\overline{TP}_L] = \frac{[\overline{TP}_i]}{1 + t_w^{1/2}}$	71	-
Reckhow (1977) $S_m = .105$	$[\overline{TP}_L] = \frac{[\overline{TP}_i]}{1.13 + .17\ t_w}$	103	$(81 < [\overline{TP}_L] < 131)$
Walker (1977) $S_m = .171$	$[\overline{TP}_L] = \frac{[\overline{TP}_i]}{1 + .824\ t_w^{.454}}$	76	$(51 < [\overline{TP}_L] < 113)$

[a] $[\overline{TP}_i]$ is $[\overline{TP}_{stream}]_{ss}$ from the Skinner-specific model, 1979 (127 mg m^{-3}).
[b] Observed $[\overline{TP}_{epi}]_{ss}$ for Skinner Lake during 1979.
[c] S_m = standard error of the estimate for the model.
[d] Where $[\overline{TP}_L]$ = average lake phosphorus concentration, $[\overline{TP}_i]$ = average streamflow phosphorus concentration and t_w = residence time of water in the lake.
[e] ± one standard error; i.e. 68% of time the true value will fall within range.

mination of the certainty expected for the model on Skinner Lake. This would provide more appropriate confidence estimates for management decisions at Skinner Lake.

A calibrated model fit to a specific lake's characteristic becomes a useful management tool. One treatment considered by planners of the Skinner Lake project was diversion of the Rimmell stream directly to the lake's outlet. Contours of the existing landscape favored such an approach. Compensation for disrupting intervening land use would have been costly. The Skinner Lake model could predict the effect of this strategy if, for example, it had been implemented in 1979. Figure 1 shows that diversion of the Rimmell would not have lowered $[\overline{TP}_{stream}]_{ss}$ appreciably. Other inlets were important in determining total $[\overline{TP}_{stream}]_{ss}$. Because the Rimmell provided a large percentage of inflow water to Skinner Lake, diverting the stream would have increased $t_{w_{ss}}$ from 0.63 to 2.35. The net effect of diverting the Rimmell would have been to reduce the $[\overline{TP}_{epi}]_{ss}$ from 63 mg m^{-3} to 45 mg m^{-3}, and $[\overline{chl\ a}]_{ss}$ from 15 mg m^{-3} to 11 mg m^{-3}. Another alternative for reducing the effect of runoff and nutrients on the lake, was a settling basin on the Rimmell stream just above its inlet to Skinner Lake. On the basis of 1979 data, if the basin removed 100% of particulate phosphorus from the water, $[\overline{TP}_{stream}]_{ss}$ would have been reduced from 127 mg m^{-3} to 52 mg m^{-3}, $[\overline{TP}_{epi}]_{ss}$ from 63 mg m^{-3} to 20 mg m^{-3}, and $[\overline{chl\ a}]_{ss}$ from 15 mg m^{-3} to 7.5 mg m^{-3}. As shown in Figure 1, this would represent a considerable improvement in water quality at Skinner Lake. Expectations in these examples provide a focus for considering costs and benefits of various strategies for land management and lake improvement.

Summary

Calibrating a general lake model for a single lake requires knowledge of the lake's specific hydrologic and limnological variables. Skinner Lake had specific attributes which were considered in development of its phosphorus:chlorophyll *a* model. Total phosphorus loading for Skinner Lake was predominantly from inlet streams. Other sources, such as atmosphere and septic tanks, had a negligible impact on relationships in the model. Flushing coefficients (ρ) during snowmelt and ice-off were >1.0 at Skinner Lake in the years of this study. Coefficients in subsequent spring overturn periods were also >1.0. $[\overline{TP}_L]$ in the ice-free period was determined during the period of spring overturn just prior to stratification when $\rho \cong 1.0$, and continuing through the time of stratification. Other temperate zone lakes with high watershed area: lake area relationships may follow this pattern. Internal phosphorus loading influenced whole-lake [TP]. However algal production in Skinner Lake was related to the [TP] of the epilimnion. $[\overline{TP}_{epi}]_{ss}$ was related to stream $[\overline{TP}_i]$ in the manner described by the Skinner-specific model. The addition of internal TP load to $[\overline{TP}_i]$ was not necessary in modeling the system. Results of this study call attention to the need for site specific information on which to base cost effective land management decisions.

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References

Allan, R. J. & B. C. Kenney, 1979. Rehabilitation of eutrophic prairie lakes in Canada. Verh. int. Ver. Limnol. 20: 214–224.

Batterson, T. R. & C. D. McNabb, 1983. Arsenic in Lake Lansing, Michigan. Envir. Toxic Chem. 2: 1–17.

Chapin, J. D. & P. D. Uttormark, 1973. Atmospheric contributions of nitrogen and phosphorus. Tech. Rep. Wat. Resour. Ctr. Univ. Wis., Madison, 35 pp.

Chapra, S., 1975. Comment on: 'An empirical method of estimating the retention of phosphorus of lakes' by W. B. Kirchner and P. J. Dillon. Wat. Resour. Res. 11: 1033–1034.

Chiaudani, G. & M. Vighi, 1974. The N:P ratio and tests with Selenastrum to predict eutrophication in lakes. Wat. Res. 8: 1063–1069.

Christensen, R. G. & C. D. Wilson, 1976. Best management practices for non-point source pollution control. Rep. Semin. U.S. Envir. Prot. Ag., Chicago, Ill., 323 pp.

Edmondson, W. T., 1961. Changes in Lake Washington following an increase in nutrient income. Verh. int. Ver. Limnol. 14: 167–175.

Glandon, R. P., F. C. Payne, C. D. McNabb & T. R. Batterson, 1981. A comparison of rain-related phosphorus and nitrogen loading from urban, wetland, and agricultural sources. Wat. Res. 15: 881–887.

Hutchinson, G. E., 1957. A Treatise on Limnology, 1. Geography, Physics, and Chemistry. John Wiley & Sons, Inc., N.Y., 1015 pp.

Kirchner, W. B. & P. J. Dillon, 1975. An empirical method of estimating the retention of phosphorus in lakes. Wat. Resour. Res. 11: 182–183.

Lake, J. & J. Morrison, 1977. Environmental impact of land use on water quality. Final Report on the Black Creek Project (Summary). U.S. Envir. Prot. Ag., Chicago, Ill., 94 pp.

Larson, D. P. & H. T. Mercier, 1976. Phosphorus retention capacity of lakes. J. Fish. Res. Bd Can. 33: 1742–1750.

OECD, 1982. Eutrophication of waters. Monitoring, Assessment and Control. Tech. Rep. ISBN 92-64-12298-2, OECD, Paris, 154 pp.

Pearson, J., 1978. Fish management at Skinner Lake, Noble County, Indiana. Indiana Dep. Nat. Resour. Div. Fish & Wildl., Indianapolis, 18 pp.

Rawson, D. S., 1955. Morphometry as a dominant factor in the productivity of large lakes. Verh. int. Ver. Limnol. 12: 164–175.

Reckhow, K. H., 1977. Phosphorus models for lake management. Ph.D. Dissertation. Harv. Univ., Camb., Mass., 304 pp.

Reckhow, K. H., 1981. Lake data analysis and nutrient budget modeling. U.S. Envir. Prot. Ag. EPA-600/3-81-011, Corvallis, Ore., 312 pp.

Ryding, S-O. & C. Forsberg, 1980. Short-term load-response relationships in shallow, polluted lakes, p. 95–103. In J. Barica and L. R. Mur (eds.), Hypertrophic ecosystems. Junk, The Hague.

Sakamoto, M., 1966. Primary production by photoplankton community in some Japanese lakes and its dependence on lake depth. Arch. Hydrobiol. 62: 1–28.

Sawyer, C. N., 1947. Fertilization of lakes by agricultural and urban drainage. J. New Engl. Wat. Wks Ass. 61: 109–127.

Smith, V. H., 1982. The nitrogen and phosphorus dependence of algal biomass in lakes: An empirical and theoretical analysis. Limnol. Oceanogr. 27: 1101–1112.

Smith, V. H. and J. Shapiro, 1981. Chlorophyll-phosphorus relations in individual lakes. Their importance to lake restoration strategies. Envir. Sci. Technol. 15: 444–451.

Strickland, J. D. H. & T. R. Parsons, 1972. A practical handbook of seawater analysis, 2nd Ed. Fish. Res. Bd, Ottawa, Can., 310 pp.

U.S. Department of Interior Bureau of Reclamation, 1967. Water Measurement Manual. Denver, Colorado, 329 pp.

U.S. Environmental Protection Agency, 1979a. Methods for Chemical Analysis of Water and Wastes. Envir. Monit. & Support Lab., Office Res. & Dev., Cincinnati, Ohio, 460 pp.

U.S. Environmental Protection Agency, 1979b. Limnological and socioeconomic evaluation of lake restoration projects: approaches and preliminary results. Corvallis Envir. Res. Lab., Office Res. & Dev., Corvallis, Oregon, 343 pp.

Vollenweider, R. A., 1968. Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication, Rep. Orgn Economic Cooperation and Development, Paris, 274 pp.

Vollenweider, R. A., 1975. Input-output models with special reference to the phosphorus loading concept in limnology. Schweiz. Z. Hydrol. 37: 53–84.

Vollenweider, R. A., 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. Mem. Ist. Ital. Idrobiol. 33: 53–83.

Vollenweider, R. A. & J. J. Kerekes, 1980. Background and summary results of the OECD cooperative program on eutrophication. Proc. Int. Symp. Inld Wat. & Lake Restoration, U.S. Envir. Prot. Ag. Wash., D.C.: 24–36.

Walker, W. W., Jr., 1977. Some analytical methods applied to lake water quality problems. Ph.D. Dissertation. Harv. Univ., Camb., Mass., 528 pp.

Walker, W. W., Jr., 1979. Use of hypolimnetic oxygen depletion rate as a trophic state index for lakes. Wat. Resour. Res. 15: 1463–1470.

Wetzel, R. G., 1975. Limnology. W. B. Saunders & Co., Philadelphia, 743 pp.

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